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MRP.169

METEOROLOGICAL RESEARCH COMMITTEE

14th February 1944.

Work carried out on the Fortress Aircraft Allotted to H.A.F. for Meteorological Duties

by A.W.Brewer.

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1. Introduction.

1.1 In June, 1943, the Fortress Aircraft F.K.192 was allotted to H.A.F. for Meteorological Duties in continuance of the work on the "Dew Point" Hygrometer designed by Dr.Dobson F.R.S. This work was begun on the Boston aircraft formerly allotted and was described in a report upon the hygrometer (M.R.P. 126). The earlier work showed that with care the hygrometer was capable of giving consistent and reasonable readings down to frost points of about -50°C, and should work, though with greater difficulties, down to the lowest temperatures encountered in the atmosphere, about -80°C. Further development was contemplated on the hygrometer to improve its performance and facilitate its use.

1.2 The Fortress aircraft, capable of climbing about 10,000 feet higher than the Boston, that is to 37,000 ft., was therefore allocated with three specific problems in view.

1. Continuation of the development of the hygrometer for the very high altitudes.

2. Investigation of Condensation trails.

3. Investigation of the water content of the upper troposphere and lower stratosphere.

In view of the fact that this was the first time that a hygrometer, capable of use at the low temperatures involved, was available, the field of investigation of items 2 and 3 was new **ground and striking results could be expected.**

1.3 Since the aircraft arrived at Boscombe Down, about 90 hours flying have been done, of which about 70 hours have been on work directly connected with hygrometry. The flying time has been restricted partly by unserviceability and partly by the fact that in large aircraft of this kind climbs above 10/10 cloud have not so far been permitted. Most of the unserviceability has been due to two minor accidents, one when a wheel broke up apparently spontaneously as the aircraft stood on the ground and the other when an aircraft taking off just hit the top of the tail fin and caused minor damage which took some time to repair. Since November 1943, we have also had a lot of trouble with the cabin heating. It is not practicable to climb this aircraft without some heat.

1.4 At first considerable difficulty was experienced in finding a crew all of whom could withstand the physical strain of the climbs. The crew must consist of a Pilot, Flight Engineer, a rear Observer to observe trails and who is also, preferably, a Wireless Operator, and a Meteorological Observer. The choice of personnel capable of carrying out the technical duties and withstanding the physical strain of the climb is very limited. The usual procedure is to climb to ceiling, about 36,700 feet, without interruption. This takes about one hour. Observations are then made on the descent every 20 mb. between 220 mb. and 300 mb., and then at the following pressure levels: 325, 350, 400, 500, 600, 700, 800 and 900 mbs., the whole

C.P.214

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flight taking about 2½ hours, most of which is above 30,000 feet (300 mbs.) Experience has shown that it is unwise to make the observations on the climb. This is partly because the levels involve extensive adjustment of engine controls and also because by the time a high altitude is reached, the crew have become too cold and exhausted to persist in the climb to the ceiling. It may be mentioned that on account of freezing of the elevator trimmers the physical effort called for from the pilot is considerable.

1.5 As received at Boscombe Down, the aircraft had a ceiling of about 34,000 feet. This has been improved to a value well over 37,000 feet, by the removal of all guns, armour plate, turrets and the reduction of the normal fuel carried from 1,000 gallons to 700 gallons.

2. Expenditure of Flying Time.

2.1 Of the 70 hours flying time an appreciable amount has been consumed in abandoned climbs from which no useful results were obtained. Flights have been abandoned for the following reasons:-

(a) Personal troubles.
1. Bends (Mr. Brewer due to unserviceable oxygen mask)
2. Stomach Pains (Pilot)

(b) Aircraft Troubles.
3. Intercom. failure (several flights)
4. Engine failure (surgeing of No.2 Engine)
5. Cabin heating failure (several flights)
6. Engine Instrument failure (boost gauge)
7. Hygrometer failure (Blocking of the cooling jet)

Also three climbs have been made from which no useful results have been obtained, testing new and unsuccessful hygrometers. Two of these were made with the original "perspex ellipse illumination" hygrometer, which had unsatifactory jet action. The third was with a second "persepx ellipse" hygrometer. On this flight it was not realised that the perspex was giving up water, causing hoar frost to be deposited densely on the thimble outside the jet. Subsequent flights showed that it was quite practicable to use this hygrometer if the deposit outside the jet were ignored.

2.2 Of the useful flying time about 2½ hours have been spent checking the speed corrections of the thermometer and general accuracy of the thermometry, and the rest to climbs, mostly made in accordance with the procedure of 1.4 above.

3. Hygrometer Installation.

3.1 The installation, at the time of writing, in the aircraft is shown in the photograph, Fig.I. This is a temporary installation which permits the comparison of two very differently constructed hygrometers.

3.2 Both instruments are built into the navigator's table and outside air is supplied through the half inch copper tube which stretches from the instruments to the centre of the window. When only one instrument is installed (the normal arrangement) part of the air passing down this copper tube is allowed to escape into the cabin in order to ensure that

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this pipe is well ventilated and so to reduce trouble from adsorbed water upon its surface. The tube has also been cleaned in chromic acid to reduce this adsorption. The thermos flasks which contain the coolant are supported below the table by strong rubber bands.

3.3 The two instruments are very different in detail. In the right hand instrument the thimble is of aluminium, anodised and dyed black, and illumination is by means of a perspex disc. The thermometry is carried out by means of a nickel resistance thermometer wound in the grooves of a fine thread cut on the skirt of the thimble and insulated by means of the anodising. The temperature is read off by means of the balanced bridge which may be seen to the left of the hygrometers. By means of a simple change over switch this same bridge can be used to measure the outside air temperature. The outside air temperature element is a platinum resistance thermometer. The bridge is calibrated to read directly the temperature of this air temperature element and corrections have to be applied to the thimble temperature readings, partly on account of the different metal, and partly because the thimble bridge is adjusted to cover a larger, and lower, temperature range. The thimble temperature of course enables the dew point to be obtained directly without speed or other corrections. This arrangement also has the advantage of eliminating the rather delicate microammeter necessary for use with thermo-couples, and it is very much faster in response than the thermo-couples. This last point is very important.

3.4 The left hand instrument is the hygrometer used in the earlier test work on the Boston aircraft and described in the report on that work. The deposition surface is gold, the illumination is by mirrors bent approximately into elliptical shape, and the thermometry is by thermo-couples.

3.5 It may be mentioned that the first instrument is better as regards the illumination and contrast of the dew and the thermometry, while the second is better as regards the action of the jet and absence of trouble due to absorption of water by the perspex.

3.6 The external air scoop and the external pitot head for the thermo-couples are seen in the photograph, fig.2. When desired the scoop and pitot head can be protected by means of the sliding shield which in the photograph is retracted to expose them.

4. Results of Speed correction trials.

4.1 To examine the relations between the various thermometers, their speed corrections and agreement with each other, a speed trial run was carried out under 10/10 turbulent cloud. The thermo-couple hygrometer was inverted, the thimble filled with a light oil, and a standard thermometer inserted in the oil. With the thimble well lagged, the temperature was steady enough to be confident of the thermometer indicating the thimble temp/ to about 1/10°C. Then by means of the thermo-couples connected differentially to the external pitot head and the microammeter it was possible to use the system as an air temperature thermometer with a known speed correction of 100% . The other thermometers on the aircraft were two strut psychrometers, one Mk.II and one Mk.V, and a balanced bridge resistance thermometer with the element used in the radiation shield which is now standard for Prata aircraft. The element for this thermometer was first

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mounted on the belly of the aircraft about 8 feet from the nose, but trouble was experienced with it reading up to about 1°C. different from the strut psychrometers and the element was moved forward right up to the nose of the aircraft. The differences then disappeared.

4.2 The results of one speed run are shown graphically in Fig. 3, in which the differences between the different thermometers are shown plotted against $\frac{(V \text{ mph})^2}{100}$. The agreement between the various thermometers is satisfactory. The results show the speed corrections for the various thermometers to be as shown below, for which the value of α is given for each thermometer to fit the formula $T = T_o - \alpha \left(\frac{V\text{mph}}{100}\right)^2$ °C.

Thermometer	α
Forward facing pitot head	1.00 standard
Mk.II Psychrometer	.80
Mk.V "	.70

4.3 During part of the period under review the balanced bridge thermometer was sent away to be copied by a manufacturer, so that for a few climbs there was no thermometer available reading below -40°C. For these climbs the air temperatures of the Larkhill radio sonde have been used, for consistency for the whole climb. The hygrometer indicated the dewpoint depression so that any error in the temperature is not reflected in the humidity.

5. Results of Ascents - Aerodynamic Condensation Trails.

5.1 The Fortress aircraft makes trails in three ways, the familiar exhaust trail, which will be dealt with in detail later, a condensation from the propellor tips and also a condensation on the upper surfaces of the wings. These last two are often visible as the aircraft passes through moist air and on damp mornings the propellor tip condensation can be seen when the aircraft is run up. They are normally highly ephemeral but in supersaturated air the condensation on the top of the main planes can form a persistent trail. This type of trail was experienced in the Boston where it seemed to come from the propellor tips but in the Fortress the wings seem to make the main contribution. In the Boston condensation on the upper surfaces of the wings was never noticed.

5.2 These aerodynamic trails have been made twice in the Fortress. Once was before instruments were fitted and the second occasion was on 5th January 1944. As on the occasions of the formation of aerodynamic trails in the Boston aircraft, the trails were made in the neighbourhood of the broken cloud sheets of weak or dying fronts.

5.3 On 5th January at 12,000 feet, at a temperature of -13°C (8°F), the trails were made continuously just beneath a very well broken layer of Alto-cumulus. The aircraft circled for some time while humidity observations were made though, at that level and temperature, the cooling is rather violent. The hygrometer indicated a dew point depression of 0.5°F, which is reasonable in view of the fact that we were immediately below Altocumulus cloud which corresponds to a supersaturation over ice of about 10%. The trails formed a dense pattern in the sky and about ½ hour later the Altocumlus patches had dispersed and the trails were dispersing by falling out as snow. They

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vanished entirely by this mechanism in about ¾ hour.

6. Results of Ascents, Persistent Exhaust Trails.

6.1 Exhaust trails are to be divided into the two main types of persistent and non persistent trails. The truly persistent exhaust trails which persist for a long time and become Cirrus cloud have been made on two ascents in the Fortress and on these occasions supersaturation with respect to ice has been indicated by the hygrometer. Supersaturation with respect to ice has been observed on one occasion without any trail being formed. Details are tabulated below:-

Date	Ht.	Pressure	Temp. °C	Frost point °C	Supersaturation %	"Mintra" °C
		Persistent Trails formed				
7.9.43	32,000	274 mbs.	-49	-48	8%	-39
"	31,000	286 "	-45	-44	10%	-39
"	28,500	322 "	-39	-37	20%	-37
24.8.43	31,000	287 "	-49	-48	10%	-39
		No Trail Formed				
24.8.43	28,800	332 mbs.	-40	-39.5	5%	-37

This lists all occasions in which persistent trails have been formed and supersaturation observed.

6.2 The last observation in the table at 27,800 feet on 24.8.43 is interesting as no trail was formed either by the Fortress or by an accompanying Spitfire. The supersaturation is slight and may not bevreal and evidence will be given later to suggest that the Mintra is perhaps about 4°C too warm.

6.3 The climb on 24.8.43 was the only one on which a co-operation of a Spitfire has been obtained. The slow rate of climb of the Fortress and the short endurance of the Spitfire are the main difficulty. A "rendez-vous" was arranged with a Spitfire at 30,000 feet on one occasion but we failed to meet.

7. Non Persistent Exhaust Trails.

7.1 Goldie has shown that below a certain temperature a trail is to be expected according to the relative humidity. The relation between this temperature and height have been given in M.R.P.116. This temperature is commonly called the "Mintra" temperature. The evidence given above suggests that the persistent trail is formed only under conditions of complete saturation or supersaturation with respect to ice.

7.2 Non persistent trails have been formed on all but one of our ascents. On the one ascent the stratosphere was so warm and dry that none was formed even in the stratosphere.

7.3 There is no exact time of beginning of the formation of trails as when conditions are near the boundary they can be induced by varying the mixture or by opening the throttle which increases the water vapour output while there is a lag in the heat output, so that the trail formation will depend on the past history of the aircraft and its engines. Nevertheless it is possible to show roughly the relation between temperature and dew point depression which separates conditions in which trails

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will form and will not.

7.4 In the table below are shown for the various ascents (a) the first or last observation in which a trail was formed and (b) the first or last observation of temperature and humidity of occasions when no trail was formed even though the temperature was below the "Mintra" of Goldie. The observations are made at varying heights and to reduce them all to comparable figures, the difference between the temperature and the "Mintra" temperature is also tabulated.

First or last observation with trails forming.

1 Date	2 Height	3 Temp °C	4 Description of trail.	5 Temp. dep. below Mintra. °C	6 Dew point depression °C
26.8.43	29,300	-45	Non persistent	7.3	4.5
6.9.43	30,600	-45	Very short	6.6	6.6
7.9.43	28,500	-38	Persistent	2.2	-1.7
7.9.43	30,000	-43	Short	5	3.4
24.8.43	28,800	-43	Non persistent	5.6	2.2
5.12.43	28,300	-46	Very short	9	9
22.12.43	26,600	-43	"	6.6	2.2
22.12.43	31,600	-50	Moderate	11.1	16.9
24.12.43	28.300	-48	Short	11.7	7.2
14.1.44	28.300	-49	Very short	12.8	7.2
4.2.44	26,600	-41	Short	4.5	-0.5
4.2.44	28.300	-44	Short	8.3	7.7

First or last observation without trails.

22.8.43	30,000	-45	7.5	13.0
24.8.43	28.000	-40	3.3	- 0.5
6.9.43	30,000	-44	5.9	4.4
3.10.43	30,000	-45	7.2	9.0
9.10.43	30,000	-44	7.2	14.0
5.12.43	26,600	-41	5.0	9.0
22.12.43	28.300	-45	8.3	6.6
22.12.43	33,100	-53	9.0	23,0
24.12.43	26,600	-44	7.8	10.0
14.1.43	26,600	-45	9.0	7.2
4.2.44	28.300	-44	8.3	10.0

Observations were originally reduced to the nearest whole degree Fahrenheit and in the conversion in columns 5 and 6, the whole deg.F. have been reduced to the nearest 1/10°C. The probable error of the air temperature measurement is about ½°F and the dew point 1 or 2 degrees F., becoming greater at lower temperatures.

7.5 These observations are all plotted in Fig. 4 in which the temperature depression below the "Mintra" temperature is plotted against the dew point depression. The first or last occasions where a trail was formed are marked X and the first or last occasions where no trail was formed are marked with a ⊙ It will be seen that though there is a fair amount of intermingling the dotted line devides the points roughly into occasions of trails and no trails and points which are on the wrong side of the line are never far over it, especially having regard to the difficulty of the humidity observation. There are two main features about this curve, firstly its intercept on the zero dew point depression (100% humidity) line, which is at about 4°C suggesting that the Mintra temperature of Goldie is about

/4°C

4°C too warm and secondly that it appears to be assymptotic to a line corresponding to a temperature about 13°C below the Mintra temperature. This implies that even in completely dry air a trail is formed if the temperature is about 13°C below the Mintra. It will of course be short. This means that the equivalent cross section area of the trail for a short trail is less than the 30 square metres which Goldie assumed for a Spitfire. For a trail of cross section area of 30 sq.m., which Goldie assumed, the curve would become assymptotic to a line about 20°C below "Mintra".

8. Results. Water Content of the lower Stratosphere.

8.1 The Stratosphere has been definitely reached and entered on five of our ascents. The main feature of all the ascents is a sudden and very intense fall in absolute (and therefore in relative) humidity as soon as the stratosphere is reached. The only two occasions on which we have got more than 3000 feet in the stratosphere, the air has dried beyond the range of the hygrometer and no deposit could be obtained. See figs. 6 and 7 for T.Ø grams of two ascents reaching the stratosphere.

8.2 To illustrate this drying effect the results of all ascents entering the Stratosphere have been plotted in fig.5 on a temperature height diagram but, to reduce all the ascents to a comparative condition, they are all plotted with the tropopause height and temperature shifted to the origin. It will be seen how in every case the dew point is falling off very rapidly within the stratosphere and at a rate without sign of diminution at the top of the ascent. On 22nd December (see fig. 6) at 6000 feet. into the stratosphere no deposit was obtained with a thimble temperature of -80°C, which implies a humidity of 1% or less - drier than anything yet encountered in the troposphere.

8.3 A non-saturated stratosphere has always been expected even on the assumption of a saturated tropopause and was confirmed by the normal reduction of condensation trail length on entering the stratosphere, but nothing of this sort has been visualised before. It cannot be said yet whether it is an essential feature of the stratosphere as these observations are too few and are all restricted to low tropopauses.

8.4 The question of the water vapour content of the stratosphere is very important to theoretical Meteorology, for the problem of the radiation balance of the stratosphere is still unsolved. Simpson assumed a water content of the stratosphere of 0.3 mm of water. This certainly would not be attained under conditions shown by the ascents. With a dew point of -80°C the water content is reduced to only a fraction of the carbon dioxide content at ground level.

9. Results. The water content of the tropopause.

9.1 The results of ascents made in the Boston aircraft and quoted in a previous report showed the extreme variability of the humidity of the upper air, where the humidity could vary between 10 or 20% supersaturation with respect to ice mainly in regions of dying fronts, to a relative humidity of 2% or 3% in strong subsidence regions. The results obtained in the Fortress have continued to show these features and also have shown the value of a complete ascent with the water content shown through the whole atmosphere from the earth's surface into the stratosphere. The value is enhanced by the direct display of the dew point which is a fundamental and often very conservative thermodynamic variable.

9.2 Probably the best example which we have yet had is shown in fig. 6 where the ascent of 22nd December 1943 is plotted on a temperature - Entropy diagram. Note the deep layer extending from 700 mbs. (10,000 feet.) to 325 mbs. (28,300 feet) with constant water vapour content of .07/grm/m^3 and a humidity increasing from about 3% at the bottom to about 95% at the top. The implication that subsidence has occurred through this immense depth is very strong. Presumably the process has continued for a fair period of time to permit cooling by radiation of the air, which, at the base, has a potential temperature 19°C lower than at the top, though so much cooling by radiation is difficult to understand.

9.3 Another example worth examination is the ascent on 7th September 1943 and shown as a TØgram in fig. 7. This ascent again shows a dry stratosphere but with a supersaturated layer beneath extending from the tropopause (250 mb.) to about 350 mb., and then there is a dry layer extending from 400 mbs. to 700 mbs. The observations would be quite in accordance with the idea that this layer had descended en bloc through about 200 mbs. The origin of this air judged from the Upper Air Section of the D.W.R. is between 40°N and 50°N., so that it may have originally been air beneath a tropopause at about 200 mbs. which has been pushed down by the introduction of the frontal air above it. The change from supersaturation at 330 mbs. to 4% R.H. at 400 mbs. is probably to be explained in part by the falling out of snow from the upper layer.

9.4 It is unfortunately impossible to treat these very isolated ascents synoptically and any deductions must be regarded as tentative.

10. Conclusion.

10.1 All the above demonstrates the value of the new weapon of a hygrometer which operates at all atmospheric temperatures as a means of attack upon meteorological problems. The "dew" point hygrometer is of particular and unique value in dealing with the low humidities of the subsidence layer in which if a hygrometer of the relative humidity type were employed much would be missed. For instance the significance between say 2% and 5% relative humidity could not be relied upon but the corresponding 8°C difference in the saturation temperature may be very significant and could be reliably measured.

10.2 New problems arise which may be attacked, but large numbers of these ascents, not 10, are required. Such problems are:-

a. Stratosphere.

1. Is extremely low relative humidity usual or is it always present in the stratosphere.

2. How are the low relative humidities which have been observed to be explained.

3. If very dry stratospheres are the rule in these latitudes, are they so in equatorial regions. If so, how do they arise.

4. If the low humidites are due to a photochemical process how is it that very high relative humidities or supersaturation appear stable just below the tropopause.

5. It is possible that interchange of air between the stratosphere and troposphere is only on a very small scale in spite of the large scale vertical movements which occur in the troposphere and possible in the stratosphere.

6. Data on the water and CO_2 content of the stratosphere are required for the examination of its relation to the radiation balance.

b. In the tropopause there can be no doubt that if such observations were available on a synoptic basis, much progress could be achieved.

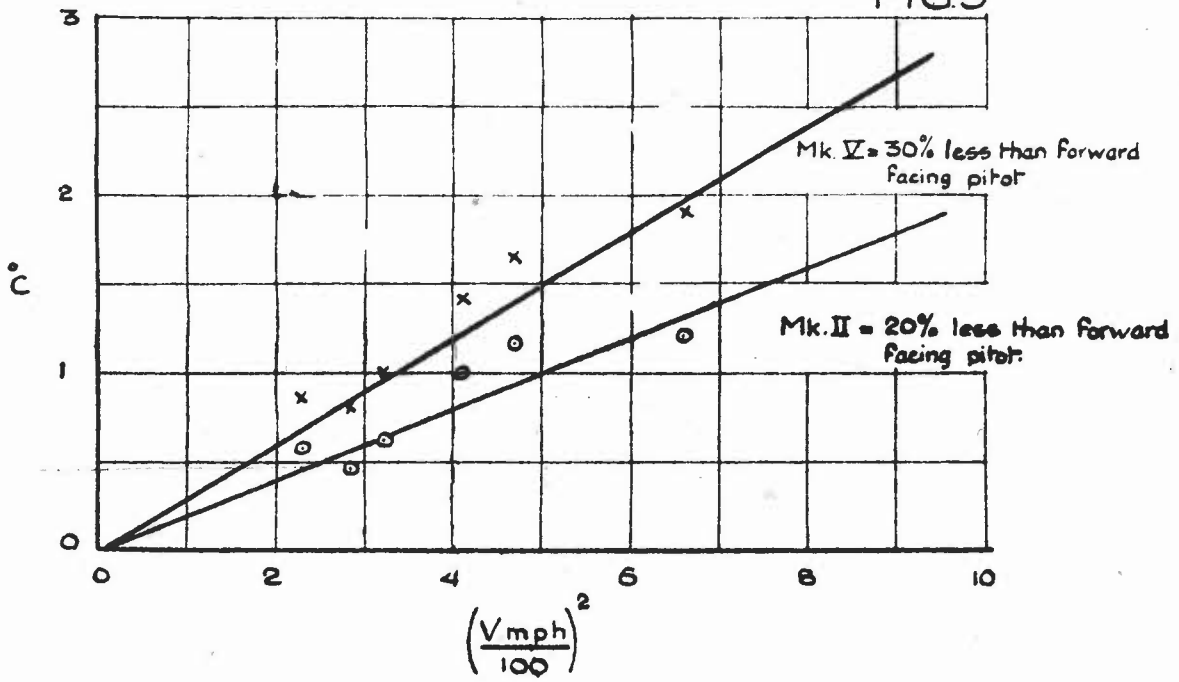
10.3 In reviewing what has been done it seems fair to say that the work on the Fortress for all its disappointments as regards serviceability, the restriction on its use above cloud, of the large crew required, and its limited ceiling, has yielded good dividends and promises great things for the future. We look forward to the day when a smaller pressure cabin aircraft can be obtained for the work, such as a Welkin or suitable Mosquito. Complete redesign of the hygrometer would be required but the additional 8000 feet or so in attainable ceiling would permit reaching the stratosphere on almost every occasion at any latitude.

SPEED CORRECTIONS TO THERMOMETERS ON FORTRESS F.K 192

⊙ = FORWARD FACING PITOT - Mk.II PSYCHROMETER DRY BULB

X = FORWARD FACING PITOT - Mk V PSYCHROMETER DRY BULB

FIG.3



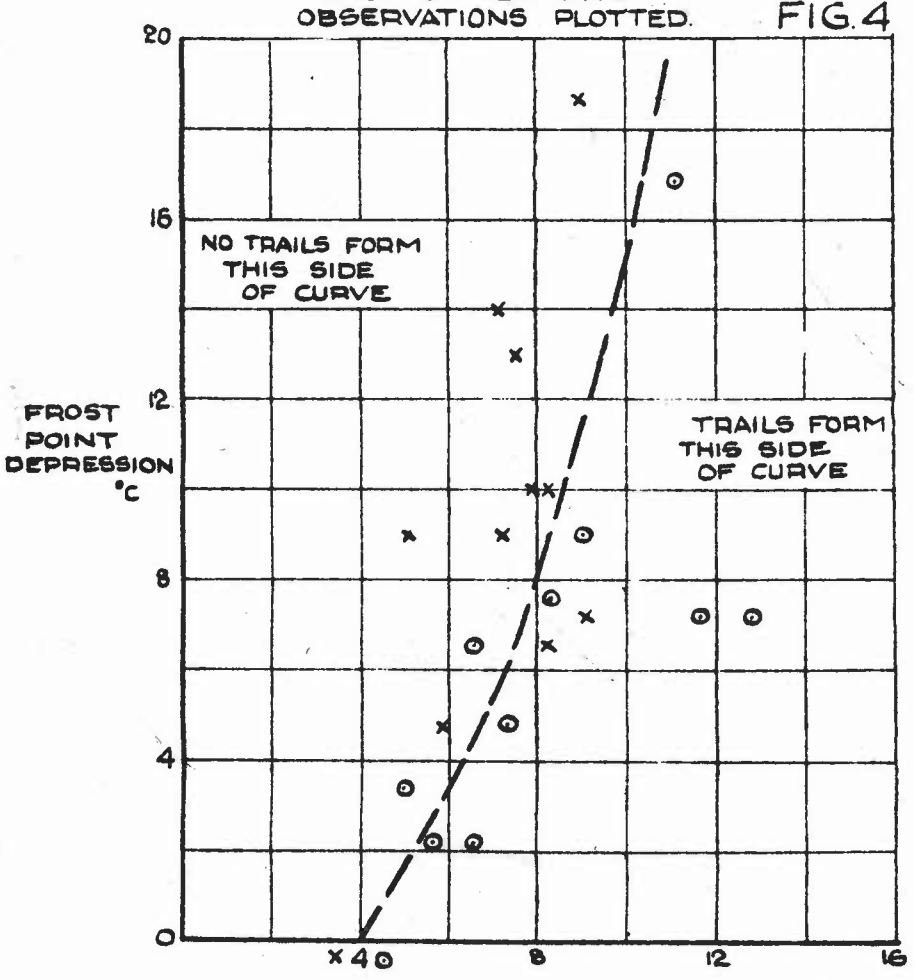
RELATION BETWEEN TRAIL COMMENCEMENT, TEMPERATURE & FROST POINT DEPRESSION.

X = NO TRAIL FORMED

⊙ = TRAILS FORMED.

ONLY BORDER LINE OBSERVATIONS PLOTTED.

FIG.4



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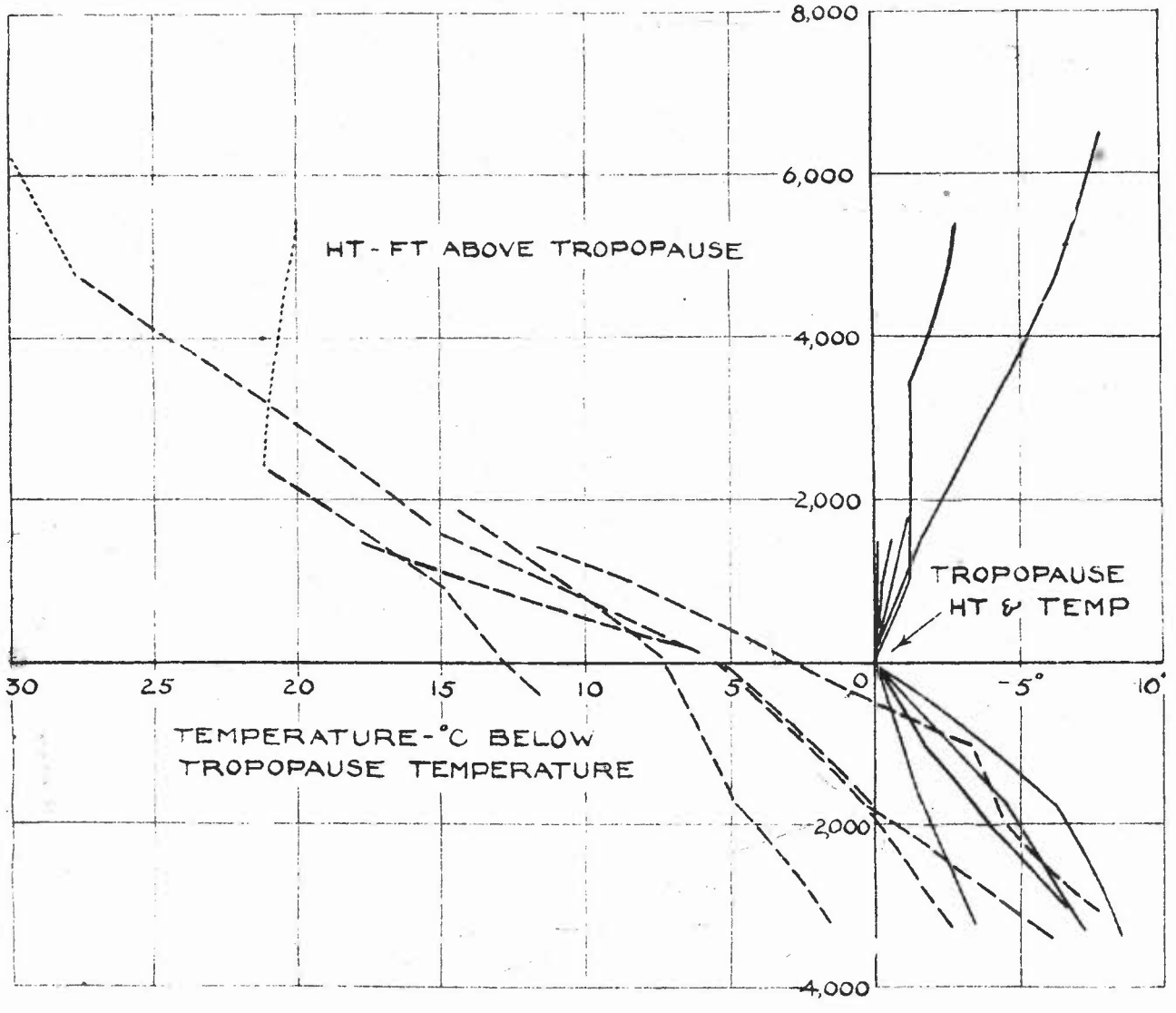
HUMIDITY IN THE STRATOSPERE. FIG. V

——— DRY BULB TEMPERATURE.
– – – – – FROST POINT TEMPERATURE
..... NO DEPOSIT OBTAINED AT THESE TEMPERATURES.



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TEPHIGRAM OF RADIO-SONDE RECORDS

STATIONS	TIMES

REMARKS

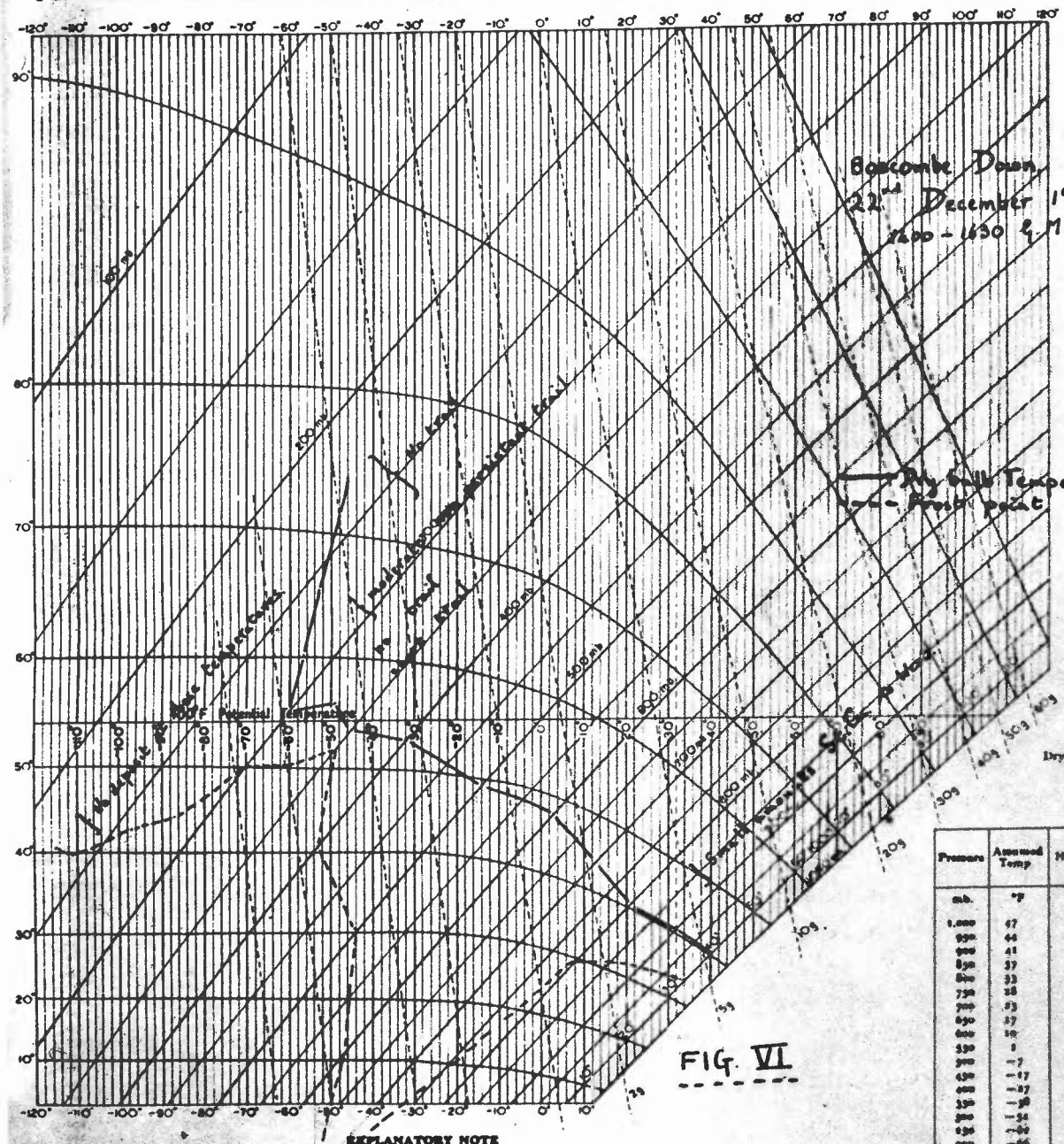

FIG. VI

Dry Adiabatic Lapse Rate is 3·3°F per 1,000 feet.

Pressure	Assumed Temp	H Height above 1,000 mb.	Increase of height due to 10°F increase in mean temperature.
mb.	°F	Feet.	Feet.
1,000	47	0	—
950	44	1,380	30
900	41	2,830	60
850	37	4,350	90
800	33	5,930	120
750	28	7,640	150
700	23	9,420	180
650	17	11,320	210
600	10	13,340	230
550	1	15,490	240
500	−7	17,810	270
450	−17	20,330	430
400	−27	23,080	490
350	−38	26,110	500
300	−51	29,530	640
250	−62	33,440	740
200	−66	38,130	800
150	−66	44,400	1,000
100	−66	52,700	1,000

Adjust heights to other surface pressures by adding (subtracting) 28 feet for every millibar of pressure above (below) 1,000 mb.

EXPLANATORY NOTE

This chart is intended for use with radio-sonde ascents to show the general features of the complete results at a glance. It is not intended for use where the main purpose of plotting the result is to examine the details in the lower part of the troposphere. The scale of the form is approximately half that of the Tephigram Form 2810.

The temperature figures printed along the 1,000 mb. line apply both to the saturated adiabatics (the curved lines) and to the temperature scales (the vertical lines). The values printed at the left hand side of the diagram apply only to the saturated adiabatics.

A straight line on the diagram gives a constant lapse rate. For an inversion the curve must cross the temperature scale from left to right. If the result of a radio sonde ascent is plotted it is usually easy to see where the stratosphere begins. It may begin as low as 400 mb.

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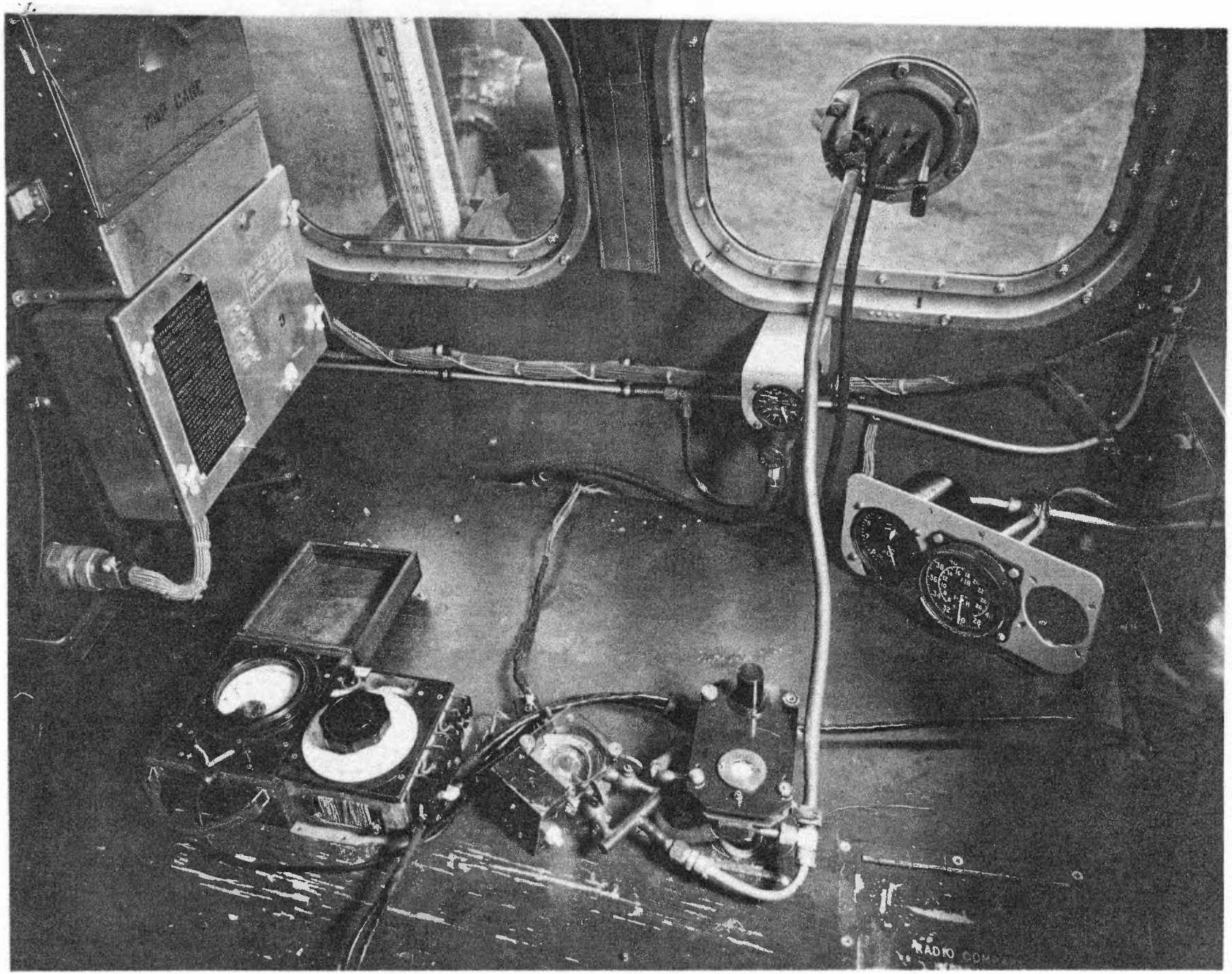

Fig. 1.